Appendix D
Hydroelectric Power Benefits Calculations

D-1. General

Traditionally, the economic feasibility of a hydroelectric project is determined by comparing the cost of the hydroelectric project to the cost of the most likely thermal alternative. In other words, is the cost of constructing and operating a hydroelectric project less than the cost of obtaining the power from the thermal power plant(s) that would be the most likely source of that power if the hydroelectric plant were not built?

D-2. Energy vs. Capacity Benefits

The following two parameters define hydroelectric project output: energy (the total amount of generation in a given time period, expressed in megawatt-hours (MWh)); and capacity (the maximum amount of power that can be delivered at any given moment, expressed in megawatts (MW)).

a. Energy benefits are measured by the cost of producing an equivalent amount of generation in the power system with the hydroelectric plant replaced by the most likely thermal alternative. The energy benefits represent the variable costs associated with producing the alternative thermal generation, which are primarily fuel costs.

b. Capacity benefits are measured as the cost of constructing an equivalent amount of thermal power plant capacity. The capacity benefits represent the capital costs and other fixed costs associated with the most likely thermal alternative.

D-3. Gain in Output Resulting from Rehabilitation Projects

The Chapter 3 of the ER 1130-2-500 establishes the policy for major rehabilitation at completed Corps projects. The Chapter 3 of the EP 1130-2-500 established guidance for the preparation and submission of Major Rehabilitation Projects Evaluation Reports for annual program and budget submissions. They should be consulted for the most recent policy on types of improvements that can be pursued under the Major Rehabilitation program and the basic assumptions for the economic analysis. The following discusses the benefit computations for the various types of improvements.

a. The first step in estimating the benefits is to determine the gain in power output that will be realized from the proposed rehabilitation plan. Rehabilitation measures can be grouped into five categories, based on the way in which they increase hydroelectric power project output:

(1) Those which restore lost efficiency.

(2) Those which restore lost capacity.

(3) Those which restore lost availability.

(4) Those which increase the remaining service life (reduce the probability of retirement).

(5) Those which increase a plant's operating flexibility.

b. Replacing the worn turbine runners is a measure that restores lost efficiency. The primary benefit of this type of rehabilitation is increased energy production. Incidental increases in efficiency can also be included in the benefits calculations. Increasing efficiency beyond that of the original equipment can be part of a rehabilitation project, but current guidance limits it to incidental or funded by non-Federal sources. Contact CECW-B for current policy regarding non-Federal funding of generation improvements.

c. Rewinding the generators with state-of-the-art materials often permits the units to operate at higher output levels. This would be an example of a capacity-increasing measure. Current guidance should be consulted to determine to what extent increased capacity can be funded under Major Rehabilitation funding. The incremental costs of improving generator capacity beyond the original project level are often very small and can in many cases be supported under the Major Rehabilitation program.

d. Replacing runners and rewinding the generators will also improve the unit availability and increase remaining service life. All of these benefits should be taken into consideration.

e. Replacing a Kaplan unit with an unreliable blade adjustment mechanism can improve the unit's response to changes in load and increase plant's flexibility.

D-4. Example

The easiest way to describe the benefit evaluation process is to walk through an example of a typical rehabilitation project. The proposed plan for the fictional "Chapman"project includes replacing all four worn turbine runners with new runners and rewinding the generator stators (Appendix C).

a. It will be assumed that when the original runners were new, the units had an average overall efficiency of 87 percent, and tests have shown that, in their current condition, the overall efficiency has dropped to 84 percent. With new runners, it is estimated that an average efficiency of 89 percent could be achieved. However, the rated capacity of the turbines remains the same.

b. The rated capacity of the original generators was 50 MW. By rewinding the generator stator with state-of-the-art materials, the rated capacity of the generators can be increased to 60 MW, which now matches more closely the maximum capability of the turbines.

D-5. Duration Curve

To graphically display the amount of energy that could be gained from a rehabilitation measure, a generation-duration curve will be used. The curve could be developed using historical records or output from a sequential streamflow routing model such as HEC-5.

a. Table D-1 shows the output of the plant by unit, and Figure D-1 shows the annual generation-duration curve for the example plant for the available period of streamflow record based on the existing condition of the plant. The duration curve in this case is based on weekly average streamflow data from a 60-year simulated operation study. Since this is a weekly average it does not reflect the effect of peaking operation. This would require an hourly generation-duration curve, which would have the same area under the curve but would show more operation at or near full output and less operation at low output levels.

b. However, for purposes of estimating energy output, a curve based on average daily, weekly, or monthly output should be used rather than an hourly curve. The use of average values is necessary to measure the amount of energy that would otherwise be spilled if the rehabilitation measure were not implemented.

c. The horizontal line at the top of the duration curve defines the maximum capacity of the plant,

Table D-1
Plant Output

Unit	Unit Capacity MW	Cumulative Capacity MW	Unit Energy MWh	Cumulative Energy, MWh
1	50	50	412,000	412,000
2	50	100	254,000	666,000
3	50	150	112,000	778,000
4	50	200	23,000	801,000

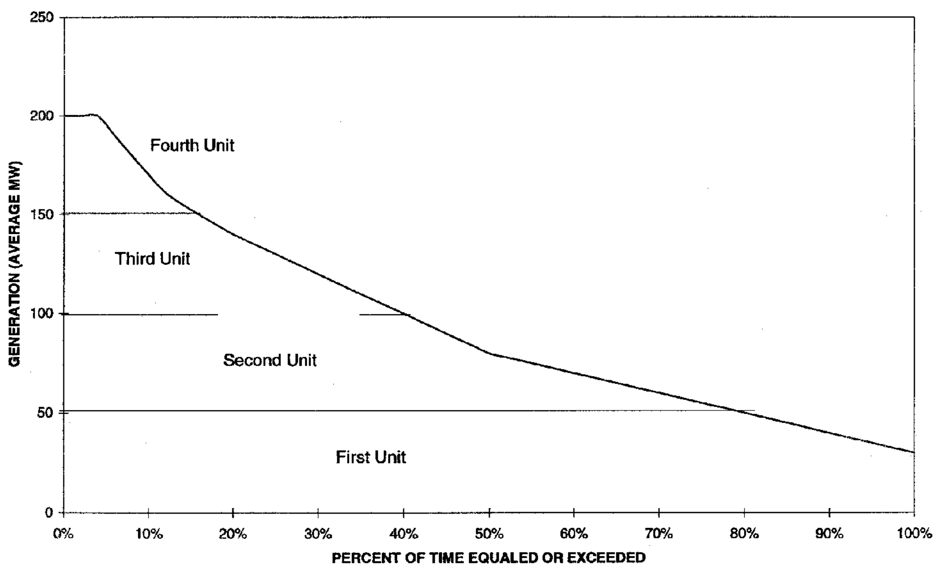

Figure D-1. Annual generation-duration curve

which in this case is 200 MW, the combined capacity of the four existing generators.

D-6. Energy Gained by New Runners

Figure D-2 describes the gain in energy achieved by replacing the worn existing turbine runners with new state-of-the-art runners. The middle curve shows the output when the original runners were new (overall efficiency of 87 percent), and the lower curve shows the output with the original runners in their existing, worn condition (overall efficiency of 84 percent). The upper curve shows the output with new state-of-the-art runners (overall efficiency of 89 percent). The area between the upper and middle curve represents the gain in energy creditable to the new runners. The upper and middle curves were derived by applying efficiency adjustment factors to each of the points that were used to derive the existing case (Figure D-1) generation-duration curve. They could also be derived through additional simulation studies with a routing modelsuch as HEC-5.

Energy output with original runners when new	828,000 MWh
Energy output with existing original runners	801,000 MWh
Energy output with new runners	845,000 MWh
Gain in energy output	44,000 MWh

Note that the capacity of the existing generators limits output to a maximum of 200 MW. So, even if the new runners had a somewhat greater megawatt capability, it would not be possible to take advantage of that capability.

D-7. Energy Gained by New Generator Windings

a. Figure D-3 describes the gain in energy achieved by rewinding the stators with state-of-the-art insulation materials. The new materials make it possible to place more copper in the windings, which increases the capacity of the generators. In this example, it is assumed that the

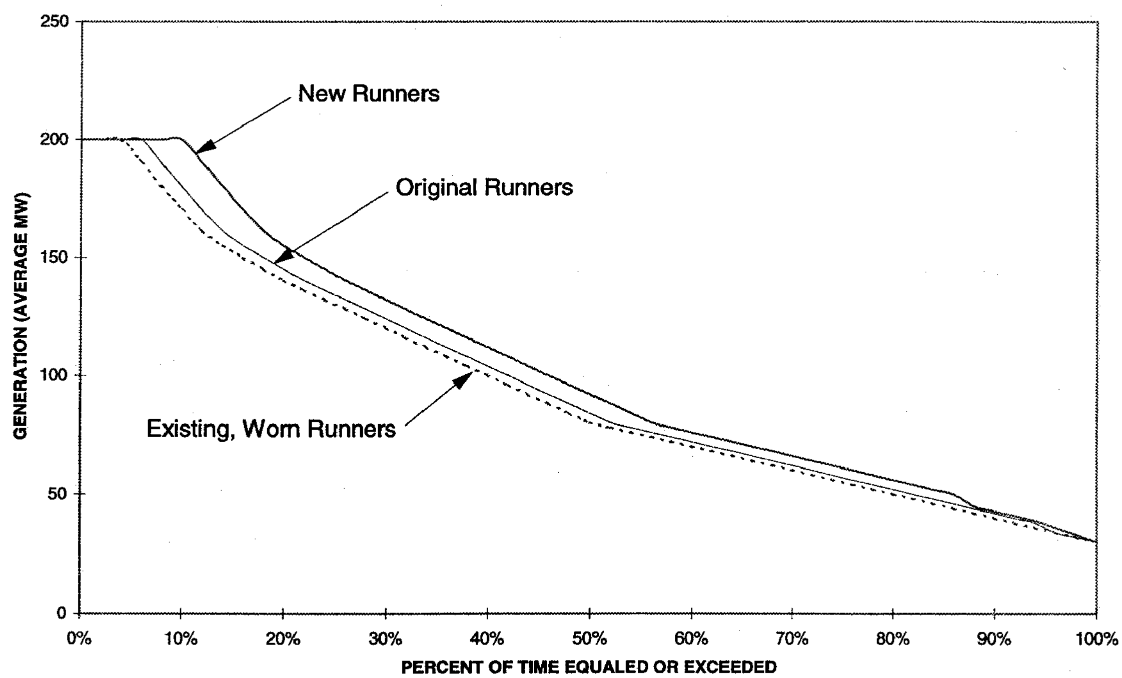

Figure D-2. Energy gain, replacing runners

new runners are in place and the capacity of the generators can be increased to match the full output of the new runners. As a result, the capacity of the plant is increased to (4 units × 60 MW) = 240 MW.

b. The upper limit (which truncates the duration curve) is increased from 200 MW to 240 MW, so the generation-duration curve was extended to the new upper limit. The upper hatched area on Figure D-3 defines the gain in energy output realized from adding a generator rewind to turbine runner replacement.

Energy output with existing generators	845,000 MWh
Energy output with generator rewind	861,000 MWh
Gain in energy output	16,000 MWh

Note that a gain in generation could also be realized by rewinding the generators but retaining the existing turbines. The upper hatched area would be smaller, being defined by an extension of the lower curve on Figure D-2 rather than the upper curve. The gain in energy for this scenario would be 4,000 MWh instead of 16,000 Mwh.

D-8. Energy Gained by Improved Availability

a. The major rehabilitation guidance prescribes the approach to evaluating the unit availability. Major elements in this analysis are the assumptions that are used to define the base condition, or the “without major rehabilitation” condition. The base condition assumes that the project will be operated in the most efficient manner possible without the proposed rehabilitation. Should the project experience unsatisfactory performance (e.g., a hydroelectric power unit outage), it is assumed that emergency funds will be available to fix the feature. The timing, frequency, and consequences of system disruptions are all unknown and must be estimated for both the with and without project conditions.

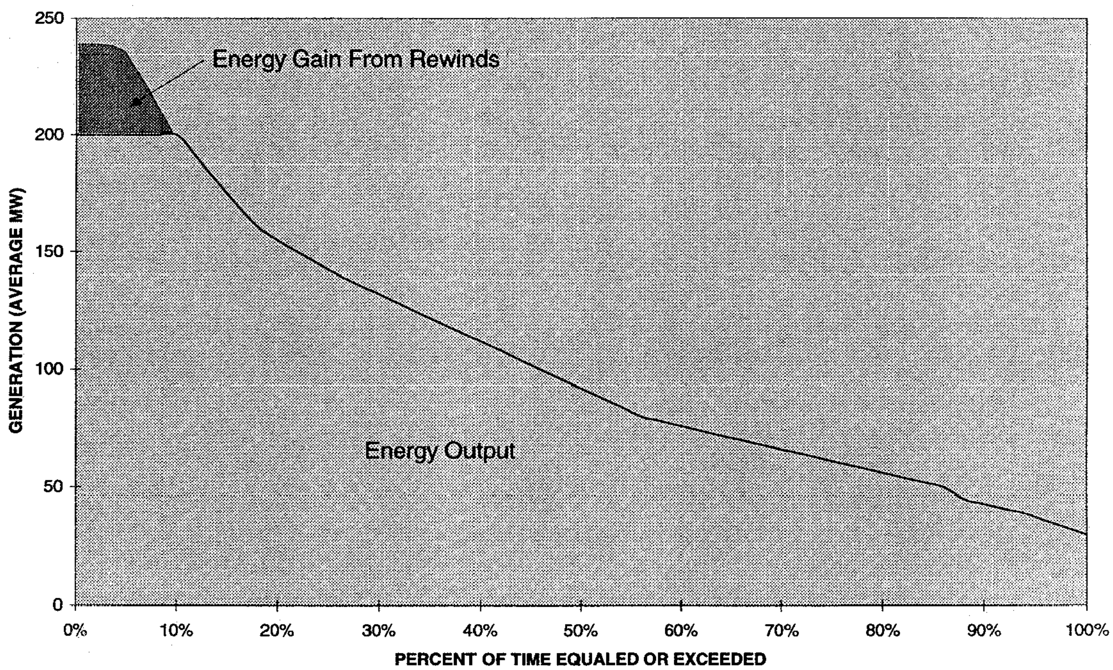

Figure D-3. Energy gain, rewinding stators

b. Both the new runners and the generator rewind could contribute to improved availability for the plant. Replacing old, failure-prone components with new components usually reduces the amount of time generating units are out of service due to forced outages. This in turn increases the amount of generation the plant can produce.

c. Figure D-4 illustrates the concept of generation loss due to forced outages. The shaded area represents the generation that would be lost if forced outages kept one unit out of service one-third of the time (high value assumed for illustrative purposes only; forced outage rates for hydroelectric plants are typically less than 10 percent). A rehabilitation measure which reduces the outage rate would reduce the size of this area, thus increasing energy output. The process of computing the loss in energy due to outages is rather complex because it is necessary to account for the combined probability characteristics of multiple components (turbine runners and generator windings, for example), the combined probabilities of different numbers of units being out of service, and the fact that component reliability tends to decrease with age. In addition, it is necessary to account for the length of the outage and the cost of repair. In order to account for all of these factors, event tree models have been developed for estimating the energy benefits attributable to reliability improvements. This topic is discussed in more detail in Appendix E. However, for purposes of illustration, it is assumed that the combined gain in average annual energy benefits due to improvement in the availability of the turbines and generators is $750,000.

D-9. Computation of Energy Benefits

The average annual gain in energy benefits that accrues to a rehabilitation plan is computed by applying a unit energy value to the gain in energy creditable to that plan. Assuming an energy value of $28/MWh, the gain in energy benefits for the runner replacement and generator rewind measures would be as follows:

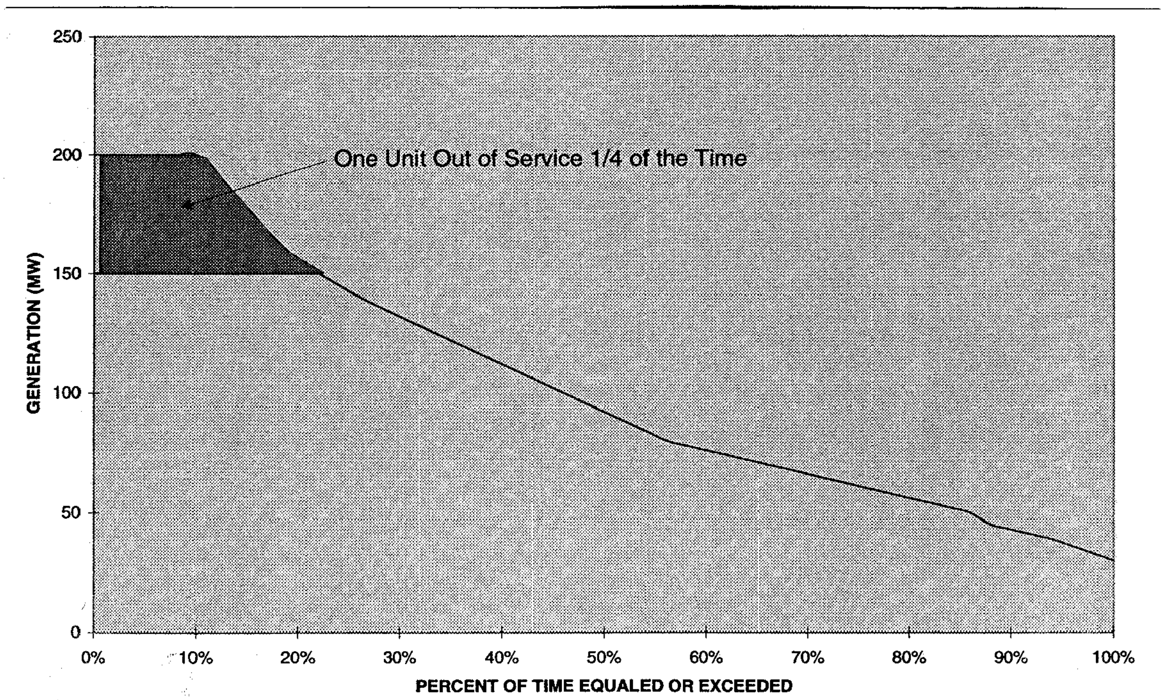

Figure D-4. Generation loss due to forced outages

Runner replacement benefits		
(44,000 MWh x $28/MWh)	=	$1,232,000
Generator rewind benefits		
(16,000 MWh x $28/MWh)	=	448,000
Availability benefits	=	750,000
Total energy benefits	=	$2,430,000

The unit energy values represent the energy cost associated with producing the generation with the most likely thermal alternative or alternatives. The energy value of $28/MWh is based on the energy values provided from the Federal Energy Regulatory Commission (FERC) for coal-fired steam, and gas-fired combustion turbines and combined cycle plants. The value is based on weighted national values by fuel source and inclusion of estimated real fuel cost escalation. The energy value is in terms of October 1995 price levels. The Corps usually develops these values using a system production cost model, simulating the operation of a particular power system twice: once with the hydroelectric plant in the system, and once with the hydroelectric plant replaced with an equivalent number of megawatts of thermal capacity. The different nature of power systems, loads, and fuel costs throughout the nation requires site-specific evaluation for each major rehabilitation study.

D-10. Dependable Capacity

a. The dependable capacity of a hydroelectric power plant is an estimate of the amount of thermal generating capacity that would carry the same amount of peak load in a power system as the hydroelectric power plant. It is intended to account for the variables that affect the amount of hydroelectric power capacity that can be used effectively in the system load, including the following:

(1) The variability in the maximum capacity that a hydroelectric power plant can deliver caused by variations in head.

(2) The variability in usable capacity caused by variations in the availability of streamflow, which in turn causes variations in the amount of energy available to support the capacity.

b. A variety of different techniques are used to estimate dependable capacity. The Corps presently uses the average availability method for projects which operate in thermal-based power systems and the critical month method for projects in hydroelectric-based power systems.

c. For this example, the average availability method was used. Space does not permit a detailed discussion of the procedure, but, in brief, it involves computing the amount of capacity that can be supported with the available energy for each week in the peak demand months for each year in the hydroelectric period of record. The average capacity that can be supported over that period defines the project's dependable capacity.

d. Supportable capacity is defined as the amount of capacity that can be supported for a specified number of hours per week. The number of hours required varies from project to project and from system to system, depending on the system resource mix and hourly load shape. A typical example might be 4 hours per day, 5 days per week (or 20 hours per week).

e. Some examples will illustrate this concept. Taking the 200-MW example project and using the 20-hr/week criterion, assume that in a particular month, sufficient stream flow is available to produce 5,000 MWh/week. Applying the 20-hr criteria, (5,000 MWh)/(20 hr/week) = 250 MW could theoretically be supported. However, the installed capacity of the plant is only 200 MW, so the supportable capacity for that month is limited to 200 MW. However, if the generators were rewound to 240 MW, the supportable capacity would increase to 240 MW. Assume that in another month, 3,000 MWh/week can be generated. In this month, only (3,000 Mwh)/(20 hr/week) = 150 MW can be supported, either with or without the rewind.

D-11. Dependable Capacity Gained by New Runners

The amount of energy available in each week will be increased due to the higher runner efficiency. In some weeks, sufficient energy is already available to support the existing capacity. But in some of the lower flow weeks, this additional energy will permit more capacity to be supported. The average gain in capacity over all of the peak demand weeks in the period of record defines the gain in dependable capacity attributable to the new runners. Typically, this gain is relatively small for runner replacement, and for this example, the new runners increase the dependable capacity from 185 MW to 190 MW (compared with an installed capacity of 200 MW).

D-12. Dependable Capacity Gained by Generator Rewind

The generator rewind increases the maximum capacity of the plant. This in turn permits more capacity to be supported in those weeks where more energy is available than is needed to support the existing capacity. In the example case, if the generator capacity is increased by 40 MW, the dependable capacity increases from 190 MW to 226 MW (compared with the new installed capacity of 240 MW).

D-13. Computation of Capacity Benefits

a. The average annual gain in capacity benefits that accrues to a rehabilitation plan is computed by applying a unit capacity value to the gain in dependable capacity creditable to that plan. Assuming a capacity value of $95/kW-year, the gain in capacity benefits for the runner replacement and rewind measures would be:

Runner replacement benefits		
(5,000 kW x $95/kW-year)	=	$ 475,000
Generator rewind benefits		
(36,000 kW x $95/kW-year)	=	<u>$3,420,000</u>
Total capacity benefits	=	$3,895,000

b. The unit capacity values represent the investment cost associated with delivering the replacement capacity with the most likely thermal alternatives. The $95/kW-year capacity value is based on a mix of coal-fired steam plants, gas-fired combined cycle plants, and gas-fired combustion turbine plants, weighted by the Energy Information Administration's projections of future capacity additions nationwide. The Corps usually obtains these values from the FERC, although they can be developed from data published by the Electric Power Research Institute (EPRI) and other sources.

D-14. Increase in Capacity Benefits Realized by Increased Availability

a. Although improving the electrical-mechanical reliability of hydroelectric generating units clearly increases the peak load-carrying capability of the units, it has proven difficult to quantitatively estimate the benefits realized from this gain. However, a relationship of generating unit average availability to effective load-carrying capability has been developed.

$$ELCC = C - \{M * \ln[(1 - R) + (R * e^{C/M})]\}$$

where

ELCC = effective load-carrying capability of unit, MW

C = rated capacity of that unit, MW

M = system characteristic (typically, 3 percent of total system capacity), MW

R = unit's equivalent forced outage rate, percent

e = 2.718

b. Using this equation, effective load carrying capabilities (ELCC's) can be developed for each unit size and each forced outage rate associated with the different proposed rehabilitation measures or plans. Ratios of ELCC are developed by dividing the ELCC for a proposed measure by the ELCC for the capacity value developed by FERC. The ratios of ELCC can then be applied to the unit capacity values to estimate the gain in capacity benefits that apply to the proposed rehabilitation measure or plan. The capacity values, as developed by FERC, already include a factor which accounts for the average availability of a typical hydropower unit compared with a thermal generating unit. For the example study, assume that the $ 95/kW-year FERC capacity value is based on a typical hydro unit availability of 93 percent, and the availability of the units in their existing condition is 91 percent. Assume that the turbine runner replacement increases the availability to 93 percent, and adding the generator rewind increases it to 95 percent. These availability values would be obtained from reliability studies.

c. While these capacity value adjustments are small, they apply to the entire dependable capacity of the plant, so they result in substantial benefits. Table D-2 summarizes the calculation of the increase in capacity unit values based on the ELCC ratios. The table also provides total benefits attributable to both the increases in dependable capacity and increases in reliability.

Table D-2
Increase in Capacity Benefits

Case	Dependable Capacity MW	Capacity Value $/kW-year	Total Benefits ($1,000)	Incremental Benefits ($1,000)
Existing	185	93	17,200	--
New Runners	190	95	18,050	850
+ Rewind	226	97	21,900	4,700

d. Subtracting out the previously calculated benefits for the gains in dependable capacity, the gain in capacity benefits as a result of improved reliability is $375,000 ($850,000 - 475,000) for the new runners alone, and $805,000 ($4,700,000 - 3,895,000) for the combined plan of new runners plus rewind.

D-15. Benefits from Increasing Remaining Service Life

The hydroelectric power benefits accruing from replacing equipment before it fails are limited to the differences in unit outage times. A planned rehabilitation program will substantially reduce the time that a unit is out of service when compared with waiting for a major equipment failure.

D-16. Flexibility Benefits

a. An additional area where benefits might accrue to power plant rehabilitation is in the area of flexibility—the ability of a power plant to come on-line quickly and to respond rapidly to changes in load. An example might be a plant with aging Kaplan units which have deteriorated to the point where the turbine blade adjustment mechanism can no longer be operated reliably. In such cases, the blades may have to be welded in a fixed position so that they lose their ability to follow load. Rehabilitating the units would restore this capability, and this in turn would generate some benefits which could be used to help support the investment in the rehabilitation work.

b. Unfortunately, while it is widely agreed that flexibility benefits are an important hydroelectric project output, it is difficult to quantify such benefits. EPRI and others have done some work in this area, but so far an accepted procedure for quantifying flexibility benefits does not exist. However, if a proposed rehabilitation project does improve a project's flexibility, this should at least be addressed qualitatively in the rehabilitation project feasibility report.

D-17. Total Gain in Benefits

The total annual power benefits attributable to the combined runner replacement/stator rewind plan would be as follows:

Energy benefits	= $2,430,000
Capacity benefits	= $4,700,000
Total benefits	= $7,130,000

D-18. Last-Added Test

a. Standard economic practice requires that separable components of multi-component plans be incrementally justified on a last-added basis. For instance, the example rehabilitation plan includes two components. For the plan to be economically feasible, both runner replacement and generator rewind would have to be individually justified on a last-added basis. This assures that the plan with the highest net National Economic Development benefits (i.e., benefits-costs) is identified, as called for in ER 1105-2-100.

b. Last-added analysis refers to a comparison of the incremental benefits gained by one component of a plan on a last-added basis, with the incremental costs of including that component in the plan. The last-added benefits for a component are determined by deducting the benefits of a plan with that component excluded from the benefits of the plan with all components included. Again referring to the example, the last-added benefits of the generator rewind would be the benefits of the total plan minus the benefits of runner replacement alone. A similar process would be followed to determine the incremental benefits of the runner replacement. Once incremental benefits are determined, they are compared to the incremental costs of including the component. If the incremental benefits exceed the incremental costs, the component is justified on a last-added basis.

D-19. Analysis Tools

Various computer analysis tools have been developed to assist in the evaluation of Major Rehabilitation and O&M repair projects. Examples of these are Hydroelectric power-REPAIR and HYDROELECTRIC POWER QUADRANT being developed through the Corps of Engineers Institute of Water Resources (CERD-IWR-R). Life-cycle, risk models have been developed by other districts such as the Portland District and Mobile District, for evaluation of Major Rehabilitation projects. These models are conceptually described in Appendix E that follows. Assistance in evaluation of the potential project benefits can be received from the Power Branch (CENPD-ET-WP) of the North Pacific Division, which is the designated Corps-wide Mandatory Center of Expertise for Hydroelectric Power System - Economic Evaluation (EC 5-1-50).